NASA TECHNICAL TRANSLATION NASA TT F-11,651

NASA TT F-11,651

SHIELDING

Technische Hochschule Stuttgart

Translation of: "Abschirmung," in:
Status Report, 1966 (Wissenschaftlicher Bericht, 1966).
May, 1967, pp. 144-159. Technische Hochschule
Stuttgart, West Germany.
Report BMwF-FBK-67-46

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JULY 1968

SHIELDING#

Technische Hochschule Stuttgart

ABSTRACT: The problem of achieving minimum radiation-shield weight while ensuring adequate protection of the payload is discussed with respect to the problem of using a nuclear reactor as a source of electrical power aboard spacecraft. Only an increase in the ratio of the reactor core height to its diameter can permit reduction of the shield volume; the H/D ratio of 1.05 used thus far is unacceptably small.

4. SHIELDING

4.1. OPTIMAL SHADOW GEOMETRY OF THE ENTIRE ASSEMBLY

(a) Fundamental Viewpoints

An important goal in the optimalization of a nuclear energy source for spacecraft is the achievement of a minimal total mass through the best possible design of individual structural components. However, it is insufficient in this regard simply to make each indivual component optimum. Moreover, it is important to determine at the same time the nature of the effect which a particular design of an individual part in the apparatus may have on all of the others. The close interaction between all of the parts means that a slight change in one direction may cause a considerable increase in the mass on the other. The mass of the shielding is especially sensitive to such changes, and even when a shadow geometry is used, it amounts to about 20% of the total mass for a system with an electrical power of 50 kW [1, 2]. /144*

The lightest possible shielding can be obtained by considering two viewpoints:

1. In a precise and reliable calculation of the radiation field of the entire apparatus.

2. Proper selection of the geometrical measurements for the entire system with respect to minimal mass for the shielding.

Careful attention paid to the first of these two points will /145

---

* Numbers in the margin indicate pagination in the foreign text.

\# Original report bears the NASA accession number N67-37907 prevent an overestimate of the radiation level in the payload and will thus enable the shield thickness and hence the mass to be reduced. The second point reflects the influence of the geometry of the system primarily on the radial dimensions of the shielding. There is a close relationship between the two viewpoints. However, precise statements regarding the geometry, which would be optimal for this shielding, can be made nearly independently of any knowledge of the radiation field.

(b) Description of Shadow Geometry

Figure 4.1 shows the "shadow geometry" in idealized form. In this figure, all of the structural components which are unimportant for an initial optimalization of the geometry (e.g., the radiator and coolant circuit) have been omitted.

The entire system is bounded by the shadow cone with a half aperture angle ϑ. Along the axis of the cone, in rotation-symmetric form, are the cylindrical reactor with its radial and axial reflectors, the shadow shield in the shape of a truncated cone, as well as the payload, represented as a circular disk. The half aperture angle ϑ of the shadow cone is determined by the radius of the reactor and payload as well as the distance between the reactor and the payload and the height of the reactor by the outermost direct beam which emerges from the reactor and strikes the payload. The cone thus produced determines the radial dimensions of the shadow shield so that all the direct beams from the reactor to the payload are shielded. Obviously, the shadow geometry is the optimum form of the arrangement for low shielding weight.

The following geometrical values are used to describe the arrangement (Fig. 4.1): /146

R_N Radius of the payload
L Distance from shielding to payload
t Thickness of shielding
t_i Thickness of the i-th particle layer of the shielding
r_0 Minimum radius of shielding
r_i Maximum diameter of the i-th layer of the shielding, in the shape of a truncated cone.
s Distance from the reactor to the shadow shield
H Height of the reactor core
D Diameter of the reactor core
$R=D/2$ Radius of the reactor core
$V_s=\pi R^2 H$ Volume of the reactor core
d Reflector thickness (cylinder coating)
d_1 Reflector thickness (frontal area of the reactor turned away from the shielding)
d_2 Reflector thickness (frontal area of the reactor turned toward the shielding).

(c) Influence of Geometrical Dimensions on the Mass of the Shadow Shield (Qualitative)

Thickness of the Shielding t

The volume of the shadow shield increases with its thickness t. The thickness is determined from the permissible dosage values to which the payload can be exposed, by calculation of the radiation field, and by the subsequent design of the shield from component layers of differens. Hence, it is dependent primarily on the estimated radiation and can therefore be used as a parameter only for purely geometrical considerations.

Distance From Shielding to Payload L

An increase in the distance L between the shielding and the payload has a reducing effect on the mass of the shielding for two reasons: on the one hand, a purely geometrically produced radiation damping is produced by increasing the distance of the payload from the radiation source, because more radiation escapes into space at the greater distance. On the other hand, the radial dimensions are effected by a reduction of the aperture angle of the shadow cone in the direction which is favorable from minimal shielding mass. /147

An increase in L, however, is limited at the upper boundary by the mass of the cross beam which increases with L, and which is required for a rigid and stable mounting of the energy source relative to the payload. At a very great distance L, therefore, the mass savings in the shield are compensated by the cross beam. For a given cross beam length, there is a minimum of the total mass for the two components (shielding and cross section)[1]. Due to the close relationship between the shield mass and L, the latter can likewise serve only as a parameter for the radiation.

Radius of the Payload, R_N

With the respect to the more favorable radial dimensions, a reduction in the size of the payload acts in the same direction as an increase in the distance L. A lower limit for a reduction of R_N is provided by the finite extent of the apparatus required for the mission of the spacecraft. R_N is therefore dependent on the special purpose of the payload and will therefore be treated as a parameter.

---

[1] This is a continuation of the study on the development of optimal reactor systems for supplying energy in spacecraft (INTAT-34).

Distance from the Reactor to the Shadow Shield s

A reduction of the distance between the reactor and the shadow shield is clearly favorable for a reduction of the shielding mass, because it leads to a reduction of the radial dimensions of the shield. However, limits are set to the reduction of s by the structural materials, cooling tubes, etc. Since a variation of s likewise does not leave the radiation field unchanged, s can also be treated as a parameter. /148

Height H and Diameter D of the Reactor Core

Thus far we have been talking mainly about quantities whose variation is so closely related to the radiation field of the systems that a sharp change in the dosage received in the payload results. However, the dimensions of the reactor still remain to be discussed. Since the reactor is intended to remain critical and to produce a given power (50 kW of electricity, e.g.), its dimensions cannot be altered arbitrarily. It is logical to proceed on the basis of a constant volume of the cylindrical core. A variation of the ratio of the height H to the diameter D which is not too excessive (referred to in the following as the H/D ratio), beginning with H/D = 1, involves only a slight change in the critical volume of the type of reactor under discussion. There is an optimal H/D ratio for a shielding of minimal mass and constant thickness.

Of course, the variation of H/D also involves a change in the radiation field of the entire system. However, studies by Homeyer [3] have shown that the effect on the dose in the payload and hence on the shield thickness is negligibly small. Hence, /149
the optimal reactor shape can be determined nearly exactly from purely geometrical considerations.

Reflector Thickness d, d_1, d_2

An increase in thicknesses d_1 and d of the reflector has the same effect as an increase in the radial dimensions of the shadow shield, because the limits of the shadow cone are displaced further outward. An increase in the reflector thickness d_2 has the same effect as an increase in the distance between the reactor and the shielding s, but also has a relatively strong effect on the radiation field, since it acts as an additional shield. We can also treat d, d_1 and d_2 as parameters.

(d) Optimal H/D Ratio for Different Values of the Geometric Parameters (Quantitative)

SHADOW Program

An ALGOL Program (SHADOW) was prepared for the study of the geometric parameters which we performed; it served to evaluate the input data R_N, d, d_1, d_2, s, n, L, H, R_a, ΔR, R_e, V_s, t_1, ρ_1, ... t_n, ρ_n. The following are the meanings of the symbols which were not discussed in Section (b):

- n Number of individual layers in the shielding
- R_a Minimal core radius
- R_e Maximal core radius
- ΔR Interval of the R region R_a to R_e for the output
- ρ_1 Thickness of the i-th layer.

For each value $R_a+k\Delta R \leq R_e$ (k = 0,1,...), SHADOW calculates from these data the tangent of the half aperture angle of the SHADOW cone tan ϑ, the angle ϑ, the total mass G, as well as the radii /150
r_i and the masses G_i of the individual layers in the shielding. In addition, the radius $R_{min}(R_a \leq R_{min} \leq R_e)$ of the core, which provides a minimal mass for the shielding, and the corresponding values of the total mass G_{min}, the masses $G_{i,min}$, radii $r_{i,min}$, and $(H/D_{min})$are determined.

The following formulas were employed:

[redacted] (4.1)

[redacted] (4.2)

[redacted] (4.3)

[redacted] (4.4)

[redacted] (4.5)

To determine R_{min}, the following equation will suffice:

[redacted] (4.6)

i.e., the determination of the minimum of the small radius of the shadow shield[2].

---

[2] This can be tested by showing that (for t + L $\neq$ 0) with dr_0/dR dtan ϑ/dR and all dr_i/dR all vanish. Then tan ϑ has a maximum for R = R_{min}.

Standard Configuration

The computer data to be discussed in the following are based /151 on the following standard configuration[3]

[redacted]

These dimensions were chosen in the basis of the design study performed at the IKE on an energy source for spacecraft [2]. The volume of the reactor core V_s, which remains constant in all calculations, corresponds to a reactor diameter D of 36.2 cm and a height of 38.2 cm, as well as an H/D ratio of 1.05. In our studies, we varied only the H/D ratio on the basis of the standard configuration, as well as with individual values of the parameters R_N, L, and d which differed from it.

Discussion of the Results

Figure 4.2 shows the volume of the shielding as a function of the core radius for the standard example chosen. In this case, the minimum volume of the shadow shield lies at an optimum radius of R_{min} = 10.7 cm; this corresponds to an H/D ratio of 5.18. For practical cases, we need not discuss an H/D ratio of this magnitude, however, it is obvious that the value of H/D = 1.05 (D = 36.2 cm, H = 38.2 cm) [2]) which was previously considered suitable on other grounds is extremely unsuitable. An improvement /152 of the situation can be brought about only by reducing the diameter of the core, while a reduction in H/D has an unfavorable effect. While the shift to R_{min} entails a volume saving of approximately 25% against the selection of H/D = 1.05 (not to be considered as a realistic solution), we can also save about 5% of the volume of the shielding by reducing R by about 1 cm.

This situation would be reversed if we could adjust the geometrical parameters (thus far assumed to be fixed) so that R_{min} would be larger than or at least equal to 18.1 cm. That this is not the case, even for the extreme parameter values which can still be discussed, is shown by the study which we have carried out.

Thus, in Figure 4.3 the influence of the distance of the pay-

---

3 The internal numbering of the different configurations which appears here and there on the figure is not important for understanding them.

load from the shielding upon the shield volume is shown. An increase in L, which has a favorable influence on the mass of the shielding, also produces a reduction of R_{min}. For a distance L of 20 m, there is an optimum core radius of 8.7 cm. The other extreme, a distance of 6 m, which is hardly worth consideration (apart from the fact that the radiation damping is insufficient) provides a R_{min} of 12.2 cm, a value which is still much below the value of 18.1 cm (Fig. 4.4).

Since the reduction of the payload radius R_N has a similar effect as an increase in L, a satisfactory setting for R_{min} cannot be expected even by changing R_N. Here, for R_N values between 50 and 125 cm, R_{min} lies in the range between 8.9 cm and 13.1 cm, in other words, still far from a H/D ratio of approximately 1.

A change in the reflector thickness d does have an influence on the shield volume, so that the shielding becomes larger as d increases. The effect of variation of d upon R_{min} is very small however (Fig. 4.7). Finally, the parameters s and t have only a negligible influence upon the most favorable reactor shape. /153

If we must make any quantitative statements regarding the influence of the H/D ratio upon the mass of the shielding, we must differentiate between two cases:

1. Shielding must be provided only against neutrons; it is not necessary to ensure gamma shielding.

2. Shielding from both neutrons and gamma radiation is required.

In the first case, so long as the heat shield is not also required, a shield will suffice which is made only of light lithium hydride. The saving in mass is then achieved with an improvement of the H/D value on the order of 10 kg. In the other case, however, in which a layer of a heavy element is required in addition to the LiH, a suitable selection of the H/D will provide a mass saving on the order of 100 kg. As a quantitative example we can use:

1. 60 cm LiH as a pure neutron shield.

2. 10 cm of uranium and 50 cm of LiH as a combined shield (with the uranium on the side of the shield turned toward the reactor).

The mass of the shadow shield is plotted in Figure 4.8 as a function of the radius of the core in both cases. For a shield consisting of pure LiH, there is a mass saving of 27 kg in making the change from R = 18.1 cm to R_{min} in the case of the standard example; in the case of a change of R by 1 cm, there is a saving of about 6 kg. In the case of an additional shielding against gamma radiation by using uranium, the transition from R = 18.1 cm to R_{min} provides a mass saving of 134 kg, while a change in R by 1 cm results in a saving of 30 kg.

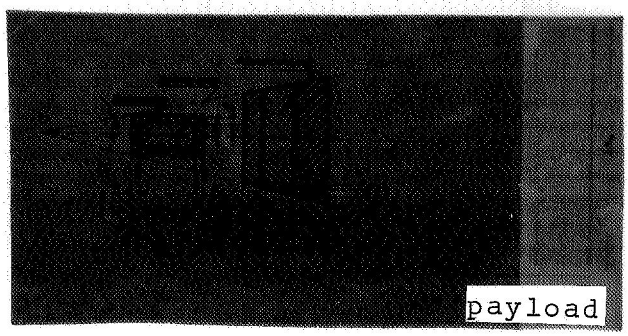

Fig. 4.1. Shadow Geometry.

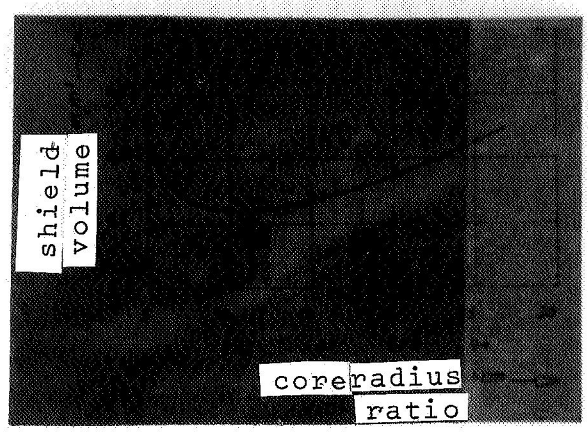

Fig. 4.2. Volume of the Shadow Shield as a Function of the Core Radius (With Constant Core Volume). /154

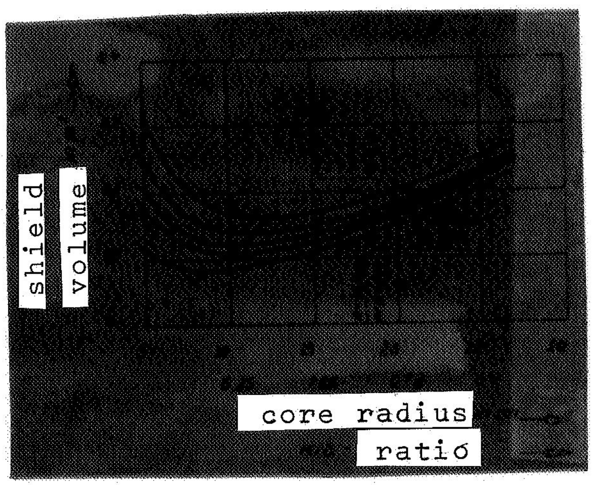

Fig. 4.3. Influence of the Distance From the Shielding to the Payload Upon the Shield Volume.

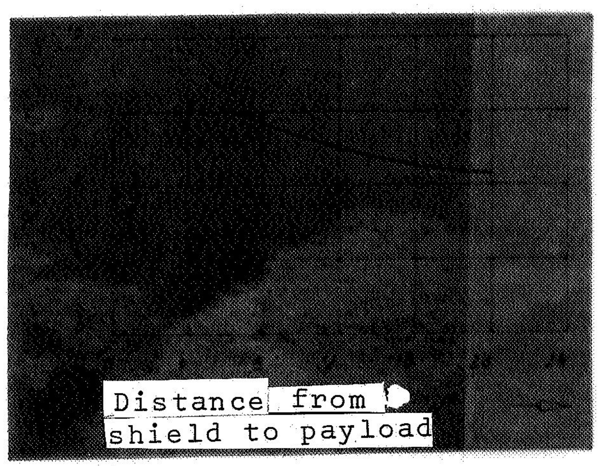

Fig. 4.4. Minimum Core Radius (R_{min}) as a Function of the Distance from the Payload. /155

(e) Summary

The present study shows that a suitable selection of the geometry for a nuclear energy power source for use on space vehicles can produce a considerable reduction in the mass of the shielding. Quantitative statements which can be made for calculating the radiation field, can be performed to give the optimal H/D ratio of the core. This shows that even in extreme cases, the previously

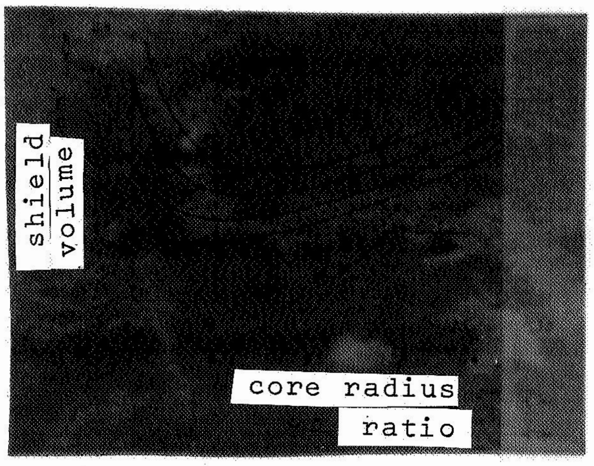

Fig. 4.5. Influence of the Payload Radius on the Shield Volume.

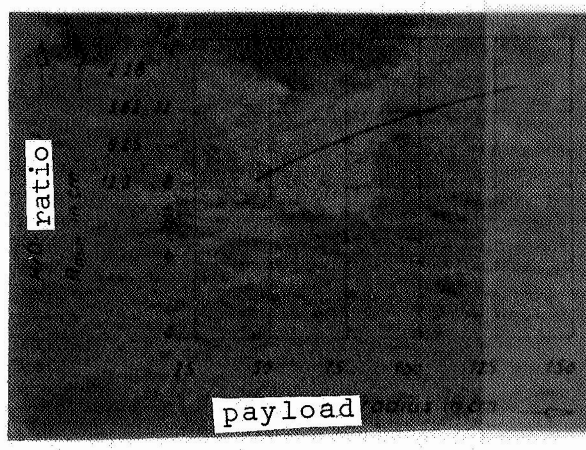

Fig. 4.6. Minimum Core Radius as a Function of the Radius of the Payload.

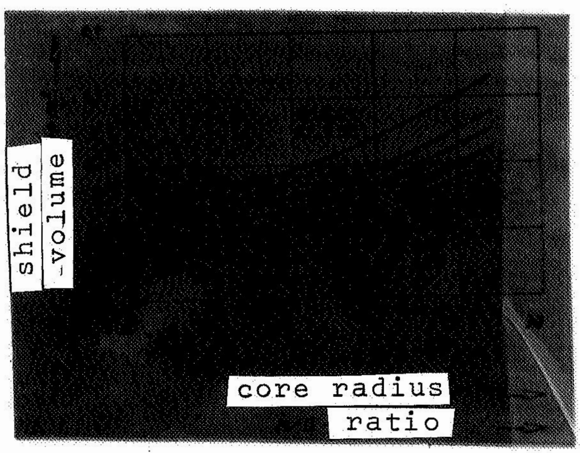

Fig. 4.7. Influence of Reflector Thickness on the Shield Volume.

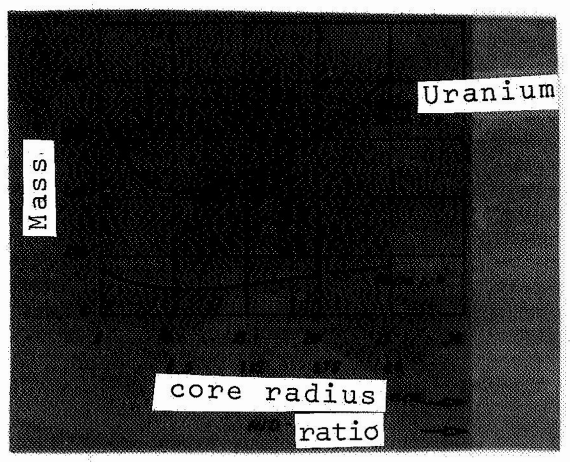

Fig. 4.8. Mass of the Shadow Shield as a Function of the Core Radius. /156

employed H/D ratio of 1.05 for a minimal shield mass is far from the optimum. /157 It is found that only an increase of the H/D ratio will permit a reduction in the volume of the shielding. Especially valuable are the savings in mass of the shadow shield for a system using lithium hydride in conjunction with a heavy element, as is required in combined shielding against neutrons and gamma rays. It should be mentioned in this regard, that the interest in achieving a low gamma radiation dose in the payload appears to be growing at this time. Therefore, an increase in the H/D ratio should by no means be excluded in advance.

4.2. Determination of Layer Thickness in a Shield; Calculation Cost and Accuracy

While the optimal conical shape of the shielding for nuclear /158
reactors for use in space vehicles can be determined by simple geometrical considerations, the minimal height of the cylindrical chamber and possible rounding off of the edges of the shielding block can be figured only by determining the radiation field.

In this respect, we must first determine whether the same calculating method can be employed for determining the layer thickness as is used for reactors on the ground. This involves primarily the question of how exact the removal concept is for determining the flux of fast neutrons. For this reason, we carried out test calculations in iron films ($\rho = 7.86$ g/cm^3) with very marked damping of fast neutrons and in sodium ($\rho = 0.8$ g/cm^3 at 600° C) with very slight damping. In both cases, it was found that the removal concept leads to considerable overdimensioning. In the case of ground-based reactors, this overdimensioning of the shielding can be accepted; the only important thing is for the calculation to ensure safety. In Tables 1 and 2, we have presented comparisons between the results of the removal concept and the precise P_L calculations. We can see that at large layer thicknesses there are considerable deviations. However, even at small layer thicknesses there can be considerable errors. From this we see that the removal concept cannot be employed for optimalization of the shielding.

We decided to employ one-dimensional geometries for the creation of a multigroup P_L program, which is comparable to an S_n program in programming expenditure, and also has three important advantages for our application: /159

1. In zero-th approximation, the P_L program contains a diffusion approximation which can also be used in the intermediary and thermal energy ranges.

2. The higher moments of the scattering cross section can be considered simply.

3. The angular distribution of the flux is considered analytically. This allows the forward components of the flux to be described better.

For routine calculations, it is important that the calculation expenditure be kept low. In this regard, we must determine how many angular moments of the flux must be considered in order to be able to get a sufficiently exact idea of the local distribution of the flux. From Figures 3 and 4 we see that both the diffusion approximation P1Q0 and the consistent P_1 approximation P1Q1 produced serious errors. For larger layer thicknesses, we get a considerable underestimate of the flux. In making the transition to the P_3 approximation, a considerable improvement results. The P_3 approximation should therefore suffice for routine calculations. From Tables 3 and 4 we can also see the influence of the initial impact source distribution, as well as the influence of the higher moments of the group scattering cross section. We see that we must also go to the P_3 approximations in the effective cross sections.

To calculate the radiation dose in the payload, it is necessary to calculate the angular distribution of the fluxes as well. Owing to the considerable distance between the shielding and the payload, this calls primarily for a small angle range in the forward direction. In order to be able to consider this angle range properly, we must go at least to the P_5 approximation of the flux in the examples calculated.

REFERENCES

1. Anderson, G.M.: Development Problems of SNAP Reactor Systems, BNL-756, 1962.
2. Haug, W., R. Fritz, R. Pruschek and E. Wolf: Atomkernenergie, 10-61, pp. 363-367, 1965.
3. Homeyer, W. G.: Shadow Shielding of Nuclear Reactor: Effect of Reactor Shape on Weight of Shield.GA 5128, 1964.

Translated for the National Aeronautics and Space Administration by:
Aztec School of Languages, Inc.,
Research Translation Division (331)
Acton, Massachusetts
NASw-1692